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Advances In Sustainable And Smart Construction Materials: A Review

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Abstract: The construction industry is facing pressing challenges of sustainability, durability, and resilience in the context of climate change and urbanization. Advanced materials such as photocatalytic cementitious composites, self-healing concretes, phase change materials (PCMs), shape-memory alloys (SMAs), and green concrete have emerged as promising solutions. This review synthesizes developments reported in the past two decades across these domains. Photocatalytic concretes enable pollution reduction and self-cleaning surfaces through TiO_2 activation. Self-healing concretes, employing bacteria, encapsulated agents, and chemical triggers, extend structural service life. PCMs provide energy-efficient building envelopes by stabilizing thermal fluctuations. SMAs enhance adaptive and repair functions in infrastructure. Finally, green concrete developments, including waste utilization and low-carbon binders, contribute toward circular economy principles. The review identifies synergies, knowledge gaps, and future opportunities for mainstream adoption of these smart and sustainable construction materials.

Keywords: Photocatalytic concrete, Self-healing concrete, Phase change materials, Shape-memory alloys, Green concrete, Sustainable construction.

I. Introduction

The construction industry contributes significantly to global energy consumption, CO_2 emissions, and environmental degradation. To address these issues, research has focused on developing innovative materials that enhance durability, self-sufficiency, and sustainability. Among the most promising developments are photocatalytic concretes capable of degrading pollutants, self-healing concretes that autonomously repair cracks, energy-efficient composites with phase change materials, adaptive structures incorporating shape-memory alloys, and environmentally friendly green concretes. These innovations collectively represent the shift toward resilient and sustainable infrastructures. This review synthesizes key advancements based on selected studies published between 2009 and 2019.

II. Photocatalytic Cementitious Composites

The incorporation of photocatalytic agents into cementitious composites represents one of the most significant advancements in sustainable construction materials. Photocatalytic cement, primarily produced by incorporating titanium dioxide (TiO_2) nanoparticles, provides self-cleaning, air-purifying, and antimicrobial properties. When exposed to ultraviolet (UV) light, TiO_2 generates electron–hole pairs that react with water and oxygen at the surface, producing hydroxyl radicals and superoxide ions. These reactive oxygen species can oxidize and decompose organic pollutants, nitrogen oxides (NOx), and volatile organic compounds (VOCs), thereby contributing to improved urban air quality.

Pacheco-Torgal and Jalali [1] offered one of the earliest comprehensive discussions on the fundamentals of photocatalytic building materials, highlighting their mechanisms and potential applications in pavements, façades, and roof tiles. They emphasized the dual functionality of such materials in both environmental remediation and aesthetic maintenance, as photocatalytic surfaces remain cleaner over time due to the decomposition of surface contaminants. Building on this foundation, Guo et al. [2] investigated how the microstructural characteristics of cement paste—such as porosity, hydration products, and pore distribution—affect NOx removal efficiency. Their results demonstrated that microstructure plays a pivotal role in determining photocatalytic performance, since it governs the accessibility of pollutants to active sites and the transport of light and reactants.

More recently, Guo, Ling, and Poon [13] provided a detailed review of TiO_2-based photocatalytic cementitious composites, consolidating advances in material modification, doping strategies to enhance visible-light activity, and large-scale applications. Their work highlighted practical uses such as self-cleaning glass, pollution-mitigating pavements, and energy-efficient building façades. They also discussed new characterization techniques for evaluating photocatalytic efficiency, including gas-phase degradation tests and surface activity measurements.

Despite these advances, several challenges remain. The long-term durability of photocatalytic coatings under mechanical abrasion, environmental soiling, and reduced UV availability (e.g., in shaded urban canyons) can limit efficiency. Additionally, the relatively high cost of TiO_2 nanoparticles and the uncertainty regarding their environmental impact pose barriers to widespread commercialization. Future research directions include the development of doped TiO_2 with enhanced visible-light responsiveness, hybrid systems combining photocatalysis with self-healing functions, and large-scale field trials to assess real-world performance.
Overall, photocatalytic cementitious composites embody a promising pathway toward integrating environmental remediation into construction materials, aligning with the broader goals of sustainable and resilient urban infrastructure.

Key Findings: Photocatalytic cementitious composites demonstrate significant potential for urban sustainability by integrating pollution mitigation with self-cleaning properties. Their performance, however, is highly dependent on UV availability, microstructural design, and long-term durability. Cost and environmental concerns associated with TiO_2 remain barriers, but ongoing advances in doping, hybridization, and field validation may accelerate practical adoption.

III. SELF-HEALING CONCRETE

Cracking in concrete is one of the most persistent and detrimental issues affecting the durability and service life of structures. Cracks allow the ingress of aggressive agents such as water, chlorides, and carbon dioxide, which accelerate reinforcement corrosion and compromise structural integrity. Traditional repair methods are costly, labor-intensive, and often temporary. To address this, researchers have developed self-healing concretes that possess the ability to autonomously repair cracks, thus extending service life and reducing maintenance costs.

One of the most pioneering approaches is bacteria-based healing, as investigated by Wiktor and Jonkers [3]. They demonstrated that specific bacterial strains, when encapsulated in protective carriers, can remain dormant in concrete until cracks allow water and oxygen ingress. Upon activation, these microorganisms precipitate calcium carbonate (calcite), which effectively seals cracks and restores watertightness. This bio-mineralization process represents a sustainable and biologically inspired solution, though its long-term viability under harsh conditions is still under evaluation.

In parallel, Pelletier et al. [4] explored microencapsulated healing agents, where capsules embedded in the cement matrix release polymers or adhesives once a crack ruptures them. This localized delivery system ensures targeted healing and has shown promising laboratory results in restoring mechanical strength. Similarly, Van Tittelboom et al. [5] tested tubular encapsulated systems, in which hollow fibers or tubes containing healing agents rupture upon crack propagation, releasing material to bond and seal the fracture. Their study quantified healing efficiency and provided insights into the influence of crack width and agent viscosity.
A broader perspective was offered by Van Tittelboom and De Belie [7], who reviewed multiple self-healing strategies including bacteria, capsules, and mineral admixtures such as expansive agents and supplementary cementitious materials. They emphasized the need for comparative performance metrics and standardized testing protocols. More recently, Sun et al. [12] reinforced the importance of self-healing composites for resilient infrastructures, focusing on their performance under cyclic mechanical loading and environmental fluctuations such as freeze–thaw cycles.

Key findings indicate that self-healing concretes can significantly extend structural lifespan, improve resilience, and minimize life-cycle costs. However, widespread adoption remains limited by scalability challenges, production costs, variability in healing efficiency, and uncertainties regarding long-term durability in real-world conditions. Future research is directed toward hybrid systems that combine multiple healing mechanisms, field-scale validation, and integration with digital monitoring technologies for performance tracking.

IV. PHASE CHANGE MATERIALS (PCMS) IN BUILDINGS

Energy consumption in buildings accounts for a major share of global electricity demand, particularly for heating, ventilation, and air conditioning (HVAC). To mitigate this, researchers have explored phase change materials (PCMs) as an innovative strategy for improving the thermal performance of building envelopes. PCMs function by absorbing and releasing latent heat during phase transitions (typically solid–liquid), thereby stabilizing indoor temperatures and reducing peak energy loads. When integrated into walls, floors, or ceilings, they provide passive thermal regulation, leading to greater occupant comfort and reduced reliance on mechanical cooling or heating systems.

Al-Saadi and Zhai [6] provided an extensive review of modeling approaches for simulating PCM-embedded building enclosures. Their study outlined numerical and analytical models used to predict heat transfer, phase transitions, and storage efficiency, which are essential for design optimization. They emphasized that model accuracy depends on incorporating PCM-specific properties such as thermal conductivity, enthalpy, and supercooling effects. Their work highlighted the importance of reliable computational tools for guiding large-scale PCM applications.

Complementing this, Memon et al. [8] offered a state-of-the-art review of PCM integration in building walls, focusing on encapsulation methods, thermal cycling stability, and compatibility with construction materials. They identified micro-encapsulation and macro-encapsulation as key strategies for preventing leakage during melting, with the former offering better distribution and surface area but at higher cost. The review also underscored the influence of climate zones on PCM effectiveness—PCMs are most beneficial in regions with high diurnal temperature variations.

Expanding further, Zhang et al. [10] discussed composite PCMs, which combine PCMs with supporting matrices such as porous concrete, polymers, or carbon-based additives. These composites enhance thermal conductivity, structural stability, and durability, addressing some of the limitations of conventional PCMs. Their review also included mathematical modeling methods for predicting PCM behavior and emphasized practical applications ranging from residential housing to large-scale commercial buildings.

Key findings suggest that PCM-enhanced materials can significantly reduce HVAC energy demand, flatten peak load curves, and contribute to low-carbon building design. However, challenges remain in terms of high material cost, thermal conductivity limitations, and performance degradation over repeated thermal cycles. Future research is expected to focus on cost-effective encapsulation, hybrid PCM systems with improved conductivity, and field-scale demonstrations in diverse climatic conditions.

V. SHAPE-MEMORY ALLOYS (SMAs) IN CONSTRUCTION

Shape-memory alloys (SMAs) are a class of smart materials that have attracted considerable interest in civil engineering due to their unique ability to undergo reversible phase transformations. These alloys, most commonly nickel–titanium (NiTi), can "remember" their original shape and return to it upon heating or stress release. This behavior arises from the reversible martensitic–austenitic transformation, which allows SMAs to recover large strains without permanent deformation. In construction, these properties translate into opportunities for self-centering, crack closure, and adaptive load-bearing functions, making SMAs highly relevant to the development of resilient infrastructure.

Graefe, Czaderski, and Motavalli [9] provided a critical review of SMA applications in construction and identified several promising areas of use. One key application is in seismic resilience, where SMA elements can provide energy dissipation and self-centering capacity in structural connections. For example, SMA dampers or braces can undergo significant cyclic deformation during an earthquake and subsequently recover their original geometry, minimizing residual displacements and reducing repair costs. Similarly, SMAs have been studied for use in prestressing tendons, where their ability to recover stress upon heating can be harnessed to apply or restore prestress without mechanical jacks.

Another innovative application lies in crack closure in reinforced concrete structures. SMA wires embedded in concrete can contract upon heating, applying compressive stresses across cracks and promoting self-repair. This concept aligns with the broader theme of smart and self-healing materials, offering a mechanical complement to chemical or biological healing strategies. Furthermore, SMAs have potential uses in adaptive façades and temperature-responsive joints, where their thermally activated properties can contribute to energy efficiency and structural adaptability.

Despite these advantages, the widespread implementation of SMAs in construction remains limited. Challenges identified by Graefe et al. [9] include the high cost of NiTi alloys, difficulties in large-scale manufacturing, and uncertainties regarding long-term durability under environmental exposure. Moreover, most applications have been demonstrated only at laboratory or pilot scale, with few examples in real-world infrastructure projects.

Key findings indicate that SMAs could play a transformative role in the future of adaptive and resilient structures. However, further progress depends on reducing material costs, developing reliable design guidelines, and conducting large-scale field demonstrations. Integration of SMAs with other smart materials, such as self-healing concretes or PCMs, may also open new pathways toward multifunctional construction systems.

VI. GREEN CONCRETE DEVELOPMENTS

Concrete is the most widely used construction material in the world, but its production is also one of the largest contributors to global CO_2 emissions, primarily due to the energy-intensive process of cement manufacturing. This has driven the evolution of green concrete, a broad category of cementitious materials designed to reduce environmental impact while maintaining or improving performance. The concept of green concrete encompasses strategies such as using industrial by-products, recycled aggregates, supplementary cementitious materials (SCMs), and alternative binders, as well as adopting carbon capture and sequestration technologies.

Andrew [11] provided a comprehensive review of recent developments in green concrete, focusing on its potential to mitigate the environmental footprint of the construction industry. The study emphasized the use of SCMs such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, and metakaolin, which partially replace ordinary Portland cement (OPC). These materials not only reduce CO_2 emissions but also improve long-term durability, mechanical strength, and resistance to aggressive environments. Additionally, the incorporation of recycled aggregates from construction and demolition waste has been shown to conserve natural resources, though challenges remain in ensuring consistent quality and mechanical performance.

Another significant avenue is the development of alternative binders, such as alkali-activated materials and geopolymers, which can eliminate the need for traditional clinker production. These binders have demonstrated excellent durability and mechanical performance, but issues such as variability in raw materials, lack of standardization, and limited large-scale applications still hinder their adoption. Emerging approaches also include the use of carbon capture and utilization (CCU), where CO_2 is directly mineralized within concrete, effectively turning the material into a carbon sink.

Andrew [11] further highlighted that the benefits of green concrete extend beyond carbon reduction. The adoption of sustainable materials also supports circular economy principles by valorizing industrial waste and reducing landfill disposal. However, trade-offs exist, particularly with respect to workability, setting time, and early-age strength, which must be balanced against environmental benefits.

Key findings suggest that while green concrete is a promising pathway toward decarbonizing the construction industry, its widespread adoption requires standardized codes, lifecycle assessment frameworks, and greater industry awareness. Future research should focus on optimizing mix designs for both performance and sustainability, as well as conducting long-term field studies to validate durability in diverse environments.

VII. DISCUSSION

The review of photocatalytic concretes, self-healing systems, phase change materials (PCMs), shape-memory alloys (SMAs), and green concretes underscores the multi-dimensional shift toward sustainable and smart construction materials. While each category addresses different aspects of durability, energy efficiency, or environmental impact, a unifying theme is the drive to extend service life, reduce maintenance, and minimize the carbon footprint of construction. A comparative overview of these materials is presented in Table 1.

Photocatalytic cementitious composites stand out for their dual role in improving aesthetics and reducing urban air pollution. However, their performance is highly dependent on light availability and surface conditions, making them more effective in certain climates and applications (Table 1). In contrast, self-healing concretes directly address the durability challenge by preventing crack propagation, thus reducing repair costs and improving structural longevity. Bacteria-based systems highlight the potential of bio-inspired solutions, while encapsulated agents offer precise, localized healing. Yet both approaches face hurdles related to cost, scalability, and long-term reliability (Table 1).

PCMs provide energy efficiency benefits by stabilizing indoor thermal conditions, aligning well with global targets for reducing building energy consumption. However, their reliance on advanced encapsulation techniques and relatively high costs has slowed adoption. Composite PCMs show promise in overcoming thermal conductivity limitations, but real-world validation is still limited (Table 1). SMAs, meanwhile, offer an entirely different paradigm of resilience by enabling adaptive and self-centering structures. Their high cost and manufacturing complexity, however, have restricted their use primarily to experimental or high-value projects (Table 1).

Green concrete, perhaps the most mature of the reviewed innovations, is central to decarbonizing the construction industry. Its reliance on industrial by-products, recycled aggregates, and alternative binders aligns with circular economy principles. However, achieving uniform performance and gaining industry-wide acceptance remain significant challenges (Table 1).

Across all categories, common barriers include cost, lack of standardized testing methods, uncertainties about long-term performance, and limited field-scale applications. Future progress will likely hinge on integrating multiple functionalities—for example, combining photocatalytic properties with self-healing mechanisms, or embedding PCMs into green concrete systems. Additionally, lifecycle assessment (LCA) frameworks, digital monitoring tools, and pilot-scale demonstrations are essential to bridge the gap between laboratory research and industry adoption.

Table 1. Comparison of Advanced Sustainable and Smart Construction Materials

Material Type	**Key Mechanism / Function**	**Main Advantages**	**Challenges / Limitations**	**Key References**
Photocatalytic Cementitious Composites	TiO_2 nanoparticles degrade pollutants under UV light (photocatalysis)	• Air pollution reduction (NOx, VOCs) • Self-cleaning surfaces • Aesthetic durability	• Dependence on UV exposure • Reduced efficiency under soiling • Cost of nanoparticles	[1], [2], [13]
Self-Healing Concrete	Healing via bacteria, microcapsules, or tubular agents	• Autonomous crack repair • Extended service life • Reduced maintenance costs	• High cost of bacteria/agents • Scalability issues • Long-term durability uncertain	[3], [4], [5], [7], [12]
Phase Change Materials (PCMs)	Store/release latent heat during solid–liquid transition	• Enhanced thermal comfort • Reduced HVAC demand • Energy efficiency in buildings	• High cost of encapsulation • Thermal conductivity limits • Performance degradation after cycles	[6], [8], [10]
Shape-Memory Alloys (SMAs)	Reversible martensitic–austenitic transformation enables shape recovery	• Self-centering after seismic loading • Crack closure capability • High resilience under cyclic stress	• High material cost (NiTi) • Limited field-scale applications • Manufacturing complexity	[9]
Green Concrete	Utilization of SCMs, recycled aggregates, and alternative binders	• Reduced CO_2 footprint • Supports circular economy •	• Variability in raw materials • Possible reduced early strength • Lack of standardization	[11]

Material Type	Key Mechanism / Function	Main Advantages	Challenges / Limitations	Key References
		Potential cost savings with waste valorization		

VIII. CONCLUSION

The transition toward sustainable and smart construction materials is no longer optional but a necessity, given the global urgency to reduce CO_2 emissions, improve resilience, and extend the life of infrastructure. This review has highlighted several material innovations—photocatalytic cementitious composites, self-healing concretes, phase change materials (PCMs), shape-memory alloys (SMAs), and green concretes—that collectively represent the forefront of construction research and practice.

Photocatalytic concretes offer a unique environmental service by mitigating air pollution and maintaining aesthetic quality through self-cleaning mechanisms. While their performance has been demonstrated in laboratory and field studies, issues of long-term durability, cost, and dependency on UV exposure remain barriers to full-scale application. Similarly, self-healing concretes have shown significant promise in reducing crack-related deterioration. From bacteria-induced calcite precipitation to encapsulated chemical agents, these systems extend service life and reduce maintenance costs, though questions about scalability and field reliability still need resolution.

PCMs contribute to energy efficiency by stabilizing indoor temperatures, directly addressing the challenge of high building energy consumption. Advances in encapsulation and composite systems are pushing this technology closer to real-world applications. SMAs, on the other hand, provide a mechanical form of resilience, enabling structures to self-center and recover after seismic or mechanical stresses. Their adoption is limited by cost and production challenges but represents an exciting frontier in adaptive infrastructure. Green concrete stands as perhaps the most immediately applicable innovation, with a clear role in reducing emissions through the use of supplementary cementitious materials, recycled aggregates, and alternative binders.

Looking forward, the **integration of multifunctional properties**—such as combining self-healing and photocatalytic functions, or embedding PCMs within green concrete systems—presents exciting opportunities. Standardized testing protocols, lifecycle assessment frameworks, and pilot projects are crucial for scaling these technologies from laboratory research to industry practice. Collaboration between academia, industry, and policymakers will be essential in accelerating adoption.

In conclusion, these innovative materials are not isolated solutions but part of a **collective movement toward sustainable, resilient, and intelligent construction systems**. By embracing and advancing them, the construction industry can play a pivotal role in addressing climate change, conserving resources, and building infrastructure that serves both present and future generations.

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